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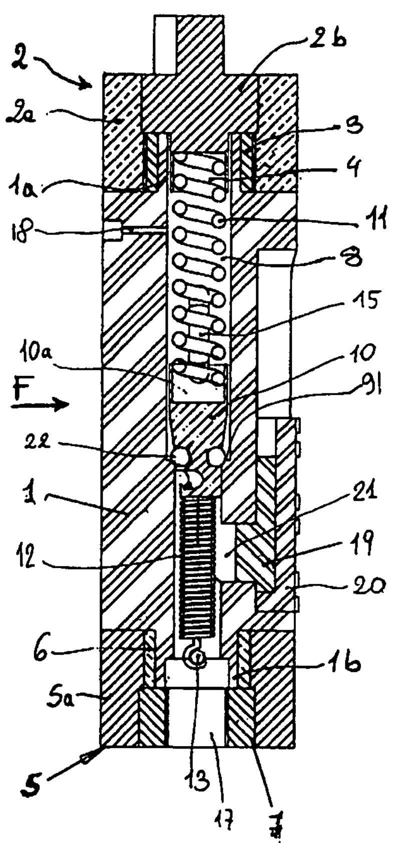
(54) **Title:** PROPORTIONAL VALVE WITH SHAPE MEMORY ALLOY (SMA) ACTUATOR



(57) **Abstract:** A proportional valve for the control of the outlet pressure of a fluid flowing therethrough comprising a valve body (1) with an inlet port (15) and an outlet port (17) for the fluid and an inner chamber (8), within which there is formed a valve seat (9) whose opening is varied by means of a shutter (10) axially movable from and towards the valve seat, the movement of the shutter being controlled by a SMA actuating member (11) acting antagonistically to elastic means (12), the temperature of the fluid being lower than the transition temperature of the shape memory alloy. The actuating member and the elastic means are connected to the valve body (1) at opposite sides with respect to the valve seat and power means (105) are provided to be activated for circulating an electric current through said actuating member to heat it by Joule effect from a temperature lower than the transition temperature to an higher one. At least a vent hole (18) for the fluid is formed on the valve body (1) for putting the part of the chamber (8) upstream of said valve seat (9) into communication with the outside or a collection network, the actuating member (11) being housed in said part of chamber in correspondence to the inlet port of the fluid, whereby a continuous flow of fluid around the actuating member is ensured for accelerating the cooling process. A closed-loop control circuit for the power means (105) is provided for controlling the circulating current as a function of a pressure signal generated by fluid pressure sensing means (19) and in such a way to offset the retarding effect produced by the fluid during the heating step of the actuating member.

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PROPORTIONAL VALVE WITH SHAPE MEMORY ALLOY (SMA) ACTUATOR

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TITLE
PROPORTIONAL VALVE WITH SHAPE MEMORY ALLOY (SMA) ACTUATOR
DESCRIPTION
Field of the Invention
The present invention relates to a proportional valve controlled by an actuator made of a shape memory alloy, particularly intended for the use with mini-and microsystem for precision pneumatic driving units and for controlled pressure gas delivery systems.

Description of the Prior Art
Valves with the actuating member made of a shape memory alloy (SMA) are already known. These alloys, generally nickel-titanium alloys, undergo a thermoelastic phase transition in the passage from the martensitic to the austenitic phase and vice versa induced by a temperature variation. Below the transition temperature (martensitic phase) the alloy can be plastically deformed and remains in this condition until it is heated up to above the transition temperature (austenitic phase), where it reversibly recovers its initial shape. In a typical configuration of this type of valve a shape memory member acts on the valve shutter against the bias of an elastic member, preferably made of steel, whose action on the shutter prevails when the temperature of the shape memory alloy member is lower than the transition temperature, while is overcome by that of the shape memory alloy member when its temperature becomes higher than the phase transition temperature.

This configuration was used mainly to design on-off type valves: see for example US patents No. 4570851, 5261597,5984195, wherein the temperature of the shape memory alloy member is directly controlled by the flowing fluid which thus controls the opening and closure of the valve. In US patents No. 4736587 and 4973024 the temperature of the shape memory alloy member is controlled by Joule effect by circulation of an electric current through it. In these examples the shape memory alloy member is in the shape of a wire or a coil spring.

Proportionally operating valves with an actuator made of a shape memory alloy heated by Joule effect have also been made. US patent No. 5865419 discloses a valve shutter which is pulled towards the valve seat by a shape memory alloy wire against the bias of a steel spring. The passage of a controlled electric current through the shape memory alloy wire controls the force exerted on the shutter and therefore the flow section of the valve. The control unit includes a PWM controller to vary the duty cycle of the electric current to be supplied to the wire, thus controlling the amount of heat produced by Joule effect in the wire and therefore the variation of the valve opening following to a variation of the linear deformation of the wire.

US patent No. 5211371 discloses a valve wherein the shutter actuator is constituted by a shape memory alloy wire arranged coaxially to a counteracting steel coil spring. The valve opening varies with the variation of the current circulating through the wire and provision is made for a control circuit based on the application of an electric drive to the SMA member to circulate a current through it capable to heat it and to operate the actuator.

The drive is performed by means of a variable frequency pulse generator as a function of a control voltage applying pulses of the same duration with variable frequency. By increasing the frequency of the pulses the power applied to the SMA member, and then the amount of heating, is increased and vice versa. The control circuit can be associated to a closed loop feedback system.

A similar valve configuration with shape memory alloy actuator and relevant electric power control circuit is disclosed in GB 2251963. The control circuit uses a PID controller and is based, inter alia, on the variation of the resistivity of the SMA member as a function of the phase transitions of the constituent material.

The main problem encountered with the valves with shape memory alloy actuator concerns the attainable degree of the control precision with respect to the response time which, of course, must be as short as possible especially when the SMA member must be returned to the austenitic phase.

Summary of the Invention

The object of the present invention is to provide a proportional valve with shape memory alloy actuator, in particular intended for the use in mini-and microsystems, capable of controlling high pressures, yet with a limited size and very low weight and with an high precision of the outlet pressure control.

Another object of the present invention is to provide a valve of the above mentioned type capable of being integrated in a compact pneumatic control unit usable in industrial and biomedical applications requiring pneumatic control systems with high performances and small overall dimensions.

These objects are reached with the proportional valve with shape memory alloy actuator according to the preamble of claim 1 and characterized in that at least a vent hole is formed on its body for putting into communication the part of the inner valve chamber upstream of the valve seat with the outside or a collection network, the actuator member being placed within said part of chamber in correspondence to the fluid inlet. In this way, it is ensured a continuous fluid flow around the shape memory alloy member thereby accelerating the cooling process when the passage of current through the actuator member is interrupted, a closed loop control circuit for the power means being provided to control the current circulating through the actuator member as a function of a pressure signal generated by means for sensing the outlet fluid pressure and in such a way to offset the retarding effect of the fluid flow during the heating of the actuator member.

In a particularly preferred solution of the invention the retarding effect of the fluid flow during the heating of the actuator member is offset by means of a controlled oversupply of the electric current flowing through the SMA member. The oversupply is applied for a time which is variable according to the initial and final position of the shutter (from 1 ms to 100 ms approximately). In this way the temperature of the SMA member is brought to a prefixed value allowing the SMA member to exert an initial force capable of offsetting the retarding effect of the fluid flow.

According to another important feature of the invention there is provided a method for the control of a valve with a shape memory alloy actuator member having the above cited characteristics consisting in providing a continuous circulation of the fluid to be controlled upstream of the valve seat, to reduce the slope of the operating curve improving the control possibility, retarding the valve opening and accelerating the closure thereof, whereby the operation of the system is linearized.

Description of the drawings

The features and the advantages of the proportional valve according to the present invention will be apparent from the following description of a non-limiting, exemplifying embodiment thereof made with reference to the attached drawings wherein: figure 1 is an axial sectional view of the valve according to the invention; figure 2 is a side view of the valve of figure 1 according to arrow F; figure 3 is a side view of the valve according to the invention axially rotated of90 with respect to the view of figure 2; figure 4 is an axial section of the valve according to the invention made along lines IV-IV of figure 3; figure 5 is a side view of the valve according to the invention made in the direction of arrow G of figure 3; figure 6 is a schematic block diagram of the power control circuit of the shape memory alloy actuating member; figure 7 shows the response of the shutter position vs time, in the presence and in the absence of a vent, when an electric current flows through the actuating member; figure 8 shows an operating mode with a large initial error in a first direction; figure 9 shows an operating mode with a large initial error in the direction opposite to that of figure 8.

Description of the preferred embodiment

With reference to figures from 1 to 5, it has been indicated at 1 a tubular body made of plastic material, constituting the main body of the valve. Body 1 is closed at one end, which will be referred as upper end hereinafter, by an upper plug 2 formed by a tubular part 2a screwed to a ring nut 3, which in turn is fixed to an axial tubular expansion la of body 1, and by a part 2b fixed to the inner side of tubular part 2a and ending with an hollow appendage 4 which engages within tubular expansion la of body 1. The other end of body 1, referred to as lower end hereinafter, is closed by a lower plug 5 formed by the tubular part 5a fixed to an axial expansion1b of body 1 through a ring nut 6 fixed to said expansion. A tubular sleeve member 7 is fixed to the inner side of tubular part 5a.

An axial chamber 8 is formed inside body 1 and is closed at its upper end from part 2b of upper plug 2. A valve seat 9 is formed at an intermediate point of chamber 8; a conical shutter 10 made of electrically conductive material is slidably engaged with seat 9. The end of shutter 10 facing toward upper plug 2 is

formed with a cavity 10a within which the end of a spring 11 is engaged, preferably ofelicoidal shape, made of shape memory alloy (SMA) axially placed in chamber 8 and abutting with the other end on part 2b of the upper plug 2 by engaging within hollow appendage 4. In particular, spring 11 is fixed to shutter 10 by means of a conductive adhesive of any known type.

A tractive spring 12, preferably made of steel, extends axially within chamber 8 between shutter 10 and lower plug 5 of body 1. More precisely, spring 12 is hooked at one end to shutter 10 and at the other end to a transverse pin 13, preferably made of steel, engaged with a support element 14 fixed to tubular part 5a of lower plug 5 and radially extending therefrom.

Two entry ports 15 for a fluid to be controlled, whose temperature is lower than the transition temperature of the shape memory alloy constituting spring11, are formed in body 1 at diametrically opposite sides and communicating with the part of chamber 8 within which spring 11 is placed. In particular, entry ports 15 have an outlet section in the shape of an axially extending slot an a circular inlet section, obtained by respective connection sleeves 16 for connecting the valve with the fluid source or the distribution network. The elongated shape of the entry ports ensures that the fluid flow, leaving chamber 8 through a vent hole 18, be constant and independent from the position of shutter 9. Furthermore, the slot-like shape has a low fluid resistance, thus resulting in a reduction of the inlet pressure drops. The outlet conduit of the controlled fluid, indicated at 17, is formed in sleeve 7 coaxially to chamber8.

A vent hole 18 puts into communication the portion of chamber 8 in which spring 11 is housed with the outside or a fluid collection network. The presence of vent hole 18 ensures the fluid circulation around spring 11 which assist in the continuous cooling thereof. In order to involve the utmost surface of spring 11 to the fluid circulation, vent hole 18 is formed at one end of body 1, in particular near to upper plug 2.

A pressure sensor 19, locked by a cover 20, is housed in a side seat 21 of body 1 which communicates with the part of chamber 8 downstream of shutter 10. Pin 13 and the part 2b of upper plug 2 are electrically connected to a power supply to allow the passage of electric current through shape memory alloy spring 11.

The valve is set to be normally closed. In fact, in the absence of an electric current circulating within spring 11, the combined effect of pressurized fluid flow through entry ports 15 and the traction exerted by spring 12, causes spring 11 to plastically elongate and then shutter 10 moves to occlude completely seat 9 of the valve.

Sealing is ensured by an 0-ring 22 placed around shutter 10.

The circulation of electric current through spring 11 causes its progressive heating due to Joule effect until the phase transition temperature is reached, at which moment spring 11 recovers its initial contracted shape overcoming the reaction of spring 12 and the fluid differential pressure, and making the shutter 10 to slide progressively away from seat 9 of the valve. The conical shape of the shutter improves the proportionality function of the valve, because a gradual increase of the cross sectional area for the controlled fluid corresponds to an axial displacement of the shutter which gives rise to a proportional reduction of the fluid resistance of the valve.

Pressure sensor 19 used with the present embodiment of invention is of the diaphragm type, wherein the pressure of the controlled fluid deforms the diaphragm and, through a pressure transducer, for example, piezoresistors, the deformation is transformed into a voltage difference, which, therefore, is directly correlated to the pressure.

Sensor 19 provides a control signal for an electric drive circuit, schematically shown in figure 6.

The diagram of figure 6 includes a block100, in particular to set the pressure value which must be controlled in an environment located downstream of the valve. The signal from the conditioning circuit 100 and the signal from a signal amplifier 102 are supplied to a conventional adder 101. The output of adder 101, through an electronic switch 107, arrives to a PID controller 103 which amplifies the error signal and handles the transfer function of the system. The signal of PID controller 103 reaches a drive circuit comprising, for example, a conventional pulse width modulator (P. W. M.) 104, which drives the power drive circuit 105 acting on block 106 consisting of the valve-sensor system and comprising SMA spring11, to which an heating current provided by the drive circuit 105 is applied. The pressure sensor 19 provides the signal correlated to the pressure downstream of shutter 10, which is amplified by amplifier 102 and is

sent to adder 101, to provide the error signal of the drive and control circuit loop consisting of blocks 101,103, 104,105,106,102.

Electronic switch 107 placed between adder 101 and controller 103 is used to discriminate the type of control to be applied (on-off or PID control). If an on-off type control is selected, the signal is such that PID controller is saturated or cut off. In other words, the purpose of the electronic switch 107 is to discriminate between small error signals, for which PID control block 103 is fully operative in the linear zone, and large error signals (positive or negative signals).

In the case of large error signals electronic switch 107, which comprises threshold circuits for its actuation (a positive threshold and a negative threshold), sends signals to blocks 103,104,105, respectively PID controller, PWM circuit and drive circuit, to actuate the system in the on-off mode. This is shown in the left part of figures 8 and 9 which will be discussed below.

A structure of the electronic switch 107 can be easily understood by a person skilled in the art and is based, for example, on the use of a pair of Schmitt triggers with respective reference thresholds of positive error and negative error. In this way it is possible to approach quickly to the valve operating point in the opening phase.

Figure 7 graphically shows the effect of the presence of vent hole 18 on the operation of the valve. As can be seen, in the absence of a vent the slope of the curve is too steep to allow an accurate and steady control without oscillations (hunting) to be carried out and the control system can substantially operate in the on-off mode only.

On the other hand, in the presence of a vent the more gradual slope of the operating curve allows to effectively operate even in the proportional mode. The cooling action generated by the fluid circulation due to the presence of a vent, which retards the response at the opening of the valve, can be easily offset by increasing the current which is passed through spring 11. The presence of a vent hole, on the other side, increases substantially, in the range of70%, the cooling power as the spring, through which the passage of current has been interrupted, is contacted by the lower temperature fluid passing through the vent hole, in this way accelerating the cooling and, therefore, the closure of the valve.

Figures 8 and 9 show the current vs time response at the opening and closure of the valve. As shown in the figures, the first part of the current response is characterized by an operation of the on-off type, during which the control circuit interacts with the system in such a way to bring the valve outlet pressure to the value of the set pressure, with an error equal to, for example, 20 mbar as an absolute value. Afterwards the control circuit adapts itself to the new situation (error lower than 20 mbar as absolute value) by operating as PID with the typical oscillating response around a value corresponding to zero error. The response of the pressure corresponding to the responses of the above mentioned currents is typical of a second order system, with the presence of a very low, possibly equal to zero, overshoot.

Variations and/or modifications can be brought to the proportional valve with shape memory alloy actuator according to the present invention, without departing from the scope of the invention as set forth in the attached claims.

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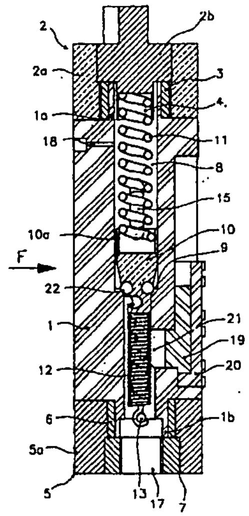

Fig.1

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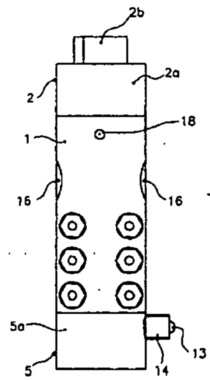

Fig.2

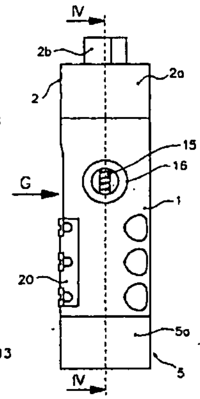

Fig.3

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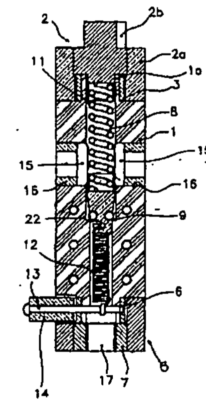

Fig.4

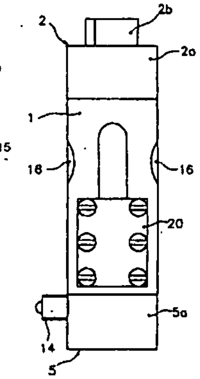

Fig.5

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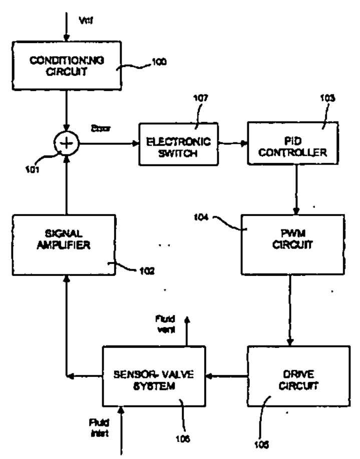

Fig. 6

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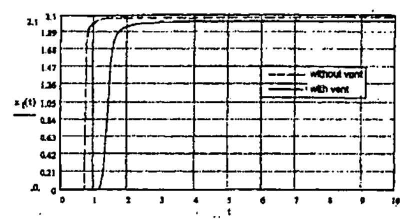

Fig. 7

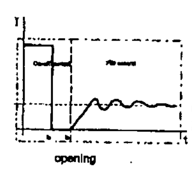

Fig. 8

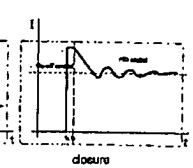

Fig. 9